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On Commutative Semigroup Rings

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I am now making a book on commutative semigroup rings. It will appear before long. This is an introduction to the book.

Thus let G be an abelian additive group which is torsion-free. A sub-semigroup S of G which contains 0 is called a grading monoid (or a g-monoid). Let R be a commutative ring, and let $R[X; S] = \{\sum_{\text{finite}} a_i X^{s_i} \mid a_i \in R, s_i \in S\}$ be the semigroup ring of S over R . Let Π be a ring-theoretical property. We will determine conditions for $R[X; S]$ to have property Π . For the present, within my knowledge and within my interest, there are 71 Theorems and 38 Propositions on $R[X; S]$ by a number of authors. We confer a number of references. The following is a part of them:

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Now we will note some theorems on commutative semigroup rings. Let G be a non-zero torsion-free abelian additive group, S be a non-zero grading monoid, R be a commutative ring, and D be an integral domain.

Let $q(S) = \{a - b \mid a, b \in S\}$. Then it is called the quotient group of

S .

Let $\alpha \in q(S)$. If $n\alpha \in S$ for some positive integer n , then α is called integral over S . If each integral element of $q(S)$ belongs to S , then S is called integrally closed.

Theorem 1 The followings are equivalent.

- (1) $D[X; S]$ is integrally closed.
- (2) D is integrally closed, and S is integrally closed.

Let $\alpha \in q(S)$. Then α is called almost integral over S , if there exists $s \in S$ such that $s + n\alpha \in S$ for each positive integer n . If each almost integral element belongs to S , then S is called completely integrally closed.

Theorem 2 The followings are equivalent.

- (1) $D[X; S]$ is completely integrally closed.
- (2) D is completely integrally closed, and S is completely integrally closed.

A non-zero divisor of R is also called a regular element. An ideal of R which contains regular elements is called a regular ideal.

The total quotient ring of R is denoted by $q(R)$.

If each finitely generated regular ideal of R is invertible, then R is called a Prüfer ring.

If each finitely generated ideal of R is principal, then R is called a Bezout ring.

If, for each $a \in R$, there exists $b \in R$ such that $a = a^2b$, then R is called a von Neumann regular ring.

Theorem 3 Let \mathbf{Q}_0 be the non-negative rational numbers. The followings are equivalent.

- (1) $R[X; S]$ is a Prüfer ring.
- (2) R is a von Neumann regular ring, and S is isomorphic onto either a subgroup of \mathbf{Q} or a subsemigroup S' of \mathbf{Q}_0 such that $q(S') \cap \mathbf{Q}_0 = S'$.
- (3) $R[X; S]$ is a Bezout ring.

If G satisfies ascending chain condition on cyclic subgroups, then G is said to satisfy ACCC.

Theorem 4 Let $G = q(S)$. The followings are equivalent.

- (1) $D[X; S]$ is a unique factorization ring.
- (2) D is a unique factorization ring, S is a unique factorization semigroup, and G satisfies ACCC.

If R satisfies ascending chain condition on regular ideals, then R is called an r-Noetherian ring.

Theorem 5 The followings are equivalent.

- (1) $R[X; S]$ is a Noetherian ring.
- (2) $R[X; S]$ is an r-Noetherian ring.
- (3) R is a Noetherian ring, and S is a finitely generated g-monoid.

Let I be a non-empty subset of $q(R)$. We set $I^{-1} = \{x \in q(R) \mid xI \subset R\}$. We set $I^v = (I^{-1})^{-1}$.

Let I be a fractional ideal of R . If $I^v = I$, then I is called divisorial.

If each divisorial ideal of D is principal, then D is called a pseudo-principal ring.

If each divisorial ideal of S is principal, then S is called a pseudo-principal semigroup.

Theorem 6 Let $G = q(S)$. The followings are equivalent.

- (1) $D[X; S]$ is a pseudo-principal ring.
- (2) D is a pseudo-principal ring, S is a pseudo-principal semigroup, and G satisfies ACCC.

Let I be an ideal of R such that $I^{k+1} = 0$ for some positive integer k . We set $d(I^i/I^{i+1}) = \min \{|X| \mid X \text{ is a set of generators of the } R\text{-module } I^i/I^{i+1}\}$ for each i ($d(0) = 0$). We set $\nu(I) = d(I/I^2) + \dots + d(I^{k-1}/I^k) + d(I^k)$.

If each finitely generated ideal of R is generated by n -elements, then R is said to have n -generator property.

Let S be a finitely generated subsemigroup of \mathbf{Q}_0 , and let $q(S) = \mathbf{Z}r$ ($r \in \mathbf{Q}_0$). Then $\min \{(1/r)S - \{0\}\}$ is called the order of S , and is denoted by $o(S)$.

Theorem 7 Let N be the nil radical of R . The followings are equivalent.

- (1) $R[X; S]$ has the n -generator property.
- (2) One of the followings holds.
 - (i) S is isomorphic onto a subgroup of \mathbf{Q} , and $\dim(R) = 0$. If I is a finitely generated ideal contained in N , there exists a decomposition $R = Re_1 \oplus \cdots \oplus Re_h$ such that $\nu(Ie_j) < n$ for each j .
 - (ii) S is isomorphic onto a subsemigroup of \mathbf{Q}_0 , $o(S) < \infty$, and $\dim(R) = 0$. If I is a finitely generated ideal contained in N , there exists a decomposition $R = Re_1 \oplus \cdots \oplus Re_h$ such that $(\nu(Ie_j) + 1)o(S) \leq n$ for each j .

If each finitely generated regular ideal is generated by n -elements, then R is said to have r - n -generator property.

If, for each regular non-unit a of R , $R/(a)$ has n -generator property, then R is said to have r - $n(1/2)$ -generator property.

If, for each non-zero and non-unit a of R , $R/(a)$ has n -generator property, then R is said to have $n(1/2)$ -generator property.

Theorem 8 The followings are equivalent.

- (1) $R[X; S]$ has $n(1/2)$ -generator property.
- (2) $R[X; S]$ has n -generator property.
- (3) $R[X; S]$ has r - $n(1/2)$ -generator property.
- (4) $R[X; S]$ has r - n -generator property.

If each ideal of R is generated by n -elements, then R is said to have rank n .

Theorem 9 Let \mathbf{Z}_0 be the non-negative integers. The followings are equivalent.

- (1) $R[X; S]$ has rank n .
- (2) One of the followings holds.
 - (i) S is isomorphic onto \mathbf{Z} , and there exists a decomposition $R = R_1 \oplus \cdots \oplus R_h$ which satisfies the following condition: If N_i is the nil radical of R_i , then $\nu(N_i) < n$, and R_i is a Noetherian local ring with maximal ideal N_i for each i .
 - (ii) S is isomorphic onto a subsemigroup of \mathbf{Z}_0 , and there exists a decomposition $R = R_1 \oplus \cdots \oplus R_h$ which satisfies the following condition: If N_i is the nil radical of R_i , then $(\nu(N_i) + 1)o(S) \leq n$, and R_i is a Noetherian local ring with maximal ideal N_i for each i .

Let K be a commutative ring with $K = q(K)$, and let Γ be a totally ordered abelian additive group. A mapping v of K onto $\Gamma \cup \{\infty\}$ is called a valuation on K if $v(x + y) \geq \inf(v(x), v(y))$, and $v(xy) = v(x) + v(y)$ for all $x, y \in K$. The subring $V = \{x \in K \mid v(x) \geq 0\}$ of K is called a valuation ring on K . t.f.r. (Γ) is called the rank of v (or of V), where t.f.r. $(\Gamma) = \max \{ |X| \mid X \text{ is a subset of } \Gamma \text{ which is linearly independent over } \mathbf{Z} \}$.

If there exists a family $\{V_\lambda \mid \lambda\}$ of valuation rings on $q(R)$ which satisfies the following conditions, then R is called a Krull ring: $R = \bigcap_\lambda V_\lambda$, each V_λ is rank 1 and discrete, and each regular element of R is a unit of V_λ for almost all λ .

Let Γ be a totally ordered abelian additive group. A mapping v of G onto Γ is called a valuation on G , if $v(x + y) = v(x) + v(y)$ for all $x, y \in G$. The subsemigroup $V = \{x \in G \mid v(x) \geq 0\}$ of G is called a valuation semigroup on G . t.f.r. (Γ) is called the rank of v (or of V).

Theorem 10 Let $G = q(S)$. The followings are equivalent.

- (1) $D[X; S]$ is a Krull ring.
- (2) D is a Krull ring, S is a Krull semigroup, and G satisfies ACCC.

Let L be an abelian additive group, and let p be a prime number. The

subgroup $\{x \in L \mid p^n x = 0 \text{ for some positive integer } n\}$ is called the p -primary component of L .

If R_M is a Noetherian ring for each maximal ideal M of R , then R is called a locally Noetherian ring.

Theorem 11 Let H be the unit group of S , and let F be a free subgroup of H such that H/F is torsion. Let Ω be the set of prime numbers p such that $p1_R$ is a non-unit of R . The followings are equivalent.

- (1) $R[X; S]$ is a locally Noetherian ring.
- (2) t.f.r. $(H) < \infty$, R is locally Noetherian, S is of the form $H + \mathbf{Z}_0 s_1 + \dots + \mathbf{Z}_0 s_n$, and the p -primary component of H/F is finite for each $p \in \Omega$.

Theorem 12 Assume that $D[X; S]$ is a Krull ring. Then

$$C(D[X; S]) \cong C(D) \oplus C(S),$$

where $C(\quad)$ denotes the divisor class group.

R is called a v-ring, if it satisfies the following condition: If I, J_1, J_2 are finitely generated ideals of R with I regular, and $(IJ_1)^v \subset (IJ_2)^v$, then $J_1^v \subset J_2^v$.

We may naturally define v-semigroup.

Theorem 13 The followings are equivalent.

- (1) $D[X; S]$ is a v-ring.
- (2) D is a v-ring, and S is a v-semigroup.

Theorem 14 Assume that D is integrally closed, and S is integrally closed. The followings are equivalent.

- (1) For each finite number of finitely generated non-zero ideals I_1, \dots, I_n of $D[X; S]$, we have $(I_1 \cap \dots \cap I_n)^v = I_1^v \cap \dots \cap I_n^v$.
- (2) For each finite number of finitely generated non-zero ideals I_1, \dots, I_n of D , we have $(I_1 \cap \dots \cap I_n)^v = I_1^v \cap \dots \cap I_n^v$, and for each finite number of finitely generated ideals I_1, \dots, I_m of S , we have $(I_1 \cap \dots \cap I_m)^v = I_1^v \cap \dots \cap I_m^v$.
- (3) $D[X; S]$ is a v-ring.

If, for each finitely generated regular ideal I of R , there exists a finitely generated regular fractional ideal J such that $(IJ)^v = R$, then R is called a Prüfer v -multiplication ring.

Theorem 15 The followings are equivalent.

- (1) $D[X; S]$ is a Prüfer v -multiplication ring.
- (2) D is a Prüfer v -multiplication ring, and S is a Prüfer v -multiplication semigroup.

Let I be a non-zero fractional ideal of R . We set $I^t = \cup \{J^v \mid J \text{ is a finitely generated fractional ideal contained in } I\}$.

Theorem 16 Assume that D is integrally closed, and S is integrally closed. The followings are equivalent.

- (1) For each finite number of non-zero ideals I_1, \dots, I_n of $D[X; S]$, we have $(I_1 \cap \dots \cap I_n)^t = I_1^t \cap \dots \cap I_n^t$.
- (2) For each finite number of non-zero ideals I_1, \dots, I_n of D , we have $(I_1 \cap \dots \cap I_n)^t = I_1^t \cap \dots \cap I_n^t$, and for each finite number of ideals I_1, \dots, I_m of S , we have $(I_1 \cap \dots \cap I_m)^t = I_1^t \cap \dots \cap I_m^t$.
- (3) $D[X; S]$ is a Prüfer v -multiplication ring.

If R satisfies the following condition, then R is called a root closed ring: If $x \in q(R)$ and $x^n \in R$ for some positive integer n , then $x \in R$.

Theorem 17 The followings are equivalent.

- (1) $D[X; S]$ is a root closed ring.
- (2) D is a root closed ring, and S is an integrally closed semigroup.

If R satisfies the following condition, then R is called a seminormal ring: If $x \in q(R)$ and $x^2, x^3 \in R$, then $x \in R$.

If S satisfies the following condition, then S is called a seminormal semigroup: If $x \in q(S)$ and $2x, 3x \in S$, then $x \in S$.

Theorem 18 The followings are equivalent.

- (1) $D[X; S]$ is seminormal.
- (2) D is seminormal, and S is seminormal.

R is called a u-closed ring, if it satisfies the following condition: If $x \in q(R)$, and $x^2 - x \in R$, $x^3 - x^2 \in R$, then $x \in R$.

Theorem 19 If D is u-closed, then $D[X; S]$ is u-closed.

An ideal of R (resp. S) is also called an integral ideal.

If D satisfies the ascending chain condition on divisorial integral ideals of D , then D is called a Mori-ring.

If D is a Mori-ring, and if, for all $a, b \in D - \{0\}$, the ideal (a, b) is divisorial, then D is called an M-ring.

We may naturally define Mori-semigroup and M-semigroup.

Theorem 20 The followings are equivalent.

- (1) $D[X; S]$ is an M-ring.
- (2) D is a field, and S is isomorphic onto an M-subsemigroup of \mathbf{Z} .

Let $F(R)$ be the set of non-zero fractional ideals of R . A mapping $*$ of $F(R)$ to $F(R)$ is called a star operation on R , if, for regular $a \in q(R)$ and $I, J \in F(R)$,

$$(a)^* = (a).$$

$$(aI)^* = aI^*.$$

$$I \subset I^*.$$

$$\text{If } I \subset J, \text{ then } I^* \subset J^*.$$

$$(I^*)^* = I^*.$$

The mapping $I \mapsto I^v = (I^{-1})^{-1}$ is a star operation called v-operation.

Assume that R is integrally closed, and let $\{V_\lambda \mid \lambda\}$ be the set of valuation overrings of R . The mapping $I \mapsto I^b = \cap_\lambda IV_\lambda$ is a star operation called b-operation.

A star operation $*$ is called an e.a.b., if it satisfies the following condition: If I, J_1, J_2 are finitely generated non-zero ideals of R with I regular,

and $(IJ_1)^* \subset (IJ_2)^*$, then $J_1^* \subset J_2^*$.

Let $F'(R)$ be the set of non-zero R -submodules of $q(R)$. A mapping $*$ of $F'(R)$ to $F'(R)$ is called a semistar operation on R , if it satisfies the following condition: For regular $a \in q(R)$ and $I, J \in F'(R)$,

$$(aI)^* = aI^*.$$

$$I \subset I^*.$$

If $I \subset J$, then $I^* \subset J^*$.

$$(I^*)^* = I^*.$$

A semistar operation $*$ of R is called e.a.b., if it satisfies the following condition: If I, J_1, J_2 are non-zero finitely generated ideals with I regular, and $(IJ_1)^* \subset (IJ_2)^*$, then $J_1^* \subset J_2^*$.

The mapping $I \mapsto I^v$ of $F'(R)$ is a semistar operation called v' -operation.

Let $\{V_\lambda \mid \lambda\}$ be the set of valuation overrings of R . The mapping $I \mapsto I^{b'} = \bigcap_\lambda IV_\lambda$ of $F'(R)$ is a semistar operation called b' -operation.

If each finitely generated regular ideal is principal, then R is called an r -Bezout ring.

Let $f = \sum a_i X^{s_i}$, where each $a_i \neq 0$, and $s_i \neq s_j$ for $i \neq j$. We set $\sum Ra_i = c(f)$.

If each regular ideal of R is generated by regular elements, then R is called a Marot ring. If R satisfies the following condition, then R is said to have Property (A): If f is a regular element of $R[X]$, then $c(f)$ is a regular ideal of R .

A denotes a Marot ring with Property (A).

Theorem 21 Let $*$ be an e.a.b. star operation on A .

Set $A_* = \{f/g \in q(A[X; S]) \mid f, g \in A[X; S] - \{0\}, g \text{ is regular, and } c(f)^* \subset c(g)^*\} \cup \{0\}$. Then,

- (1) A_* is an overring of $A[X; S]$, and $A_* \cap K = A$, where $K = q(A)$.
- (2) A_* is an r -Bezout ring.
- (3) If I is a finitely generated regular ideal of A , then $IA_* \cap K = I^*$ and $IA_* = I^* A_*$.

A multiplicative subset T of R is called a regular multiplicative subset,

if each element of T is regular.

Theorem 22 Assume that A is integrally closed. Let $T = \{f \in A[X; S] \mid c(f) = A\}$. The followings are equivalent.

- (1) A is a Prüfer ring.
- (2) $A[X; S]_T = A_b$.
- (3) $A[X; S]_T$ is a Prüfer ring.
- (4) A_b is a quotient ring of $A[X; S]$ with respect to a regular multiplicative subset.
- (5) Each prime ideal of $A[X; S]_T$ is the contraction of a prime ideal of A_b .
- (5)' Each regular prime ideal of $A[X; S]_T$ is the contraction of a prime ideal of A_b .
- (6) Each regular prime ideal of $A[X; S]_T$ is the extension of a prime ideal of A .

If each regular ideal is the product of prime ideals, then R is called a Dedekind ring.

If each regular ideal of R is principal, then R is called an r -principal ideal ring.

Theorem 23 Assume that A is integrally closed. Let $T = \{f \in A[X; S] \mid c(f) = A\}$. The followings are equivalent.

- (1) A is a Dedekind ring.
- (2) $A[X; S]_T$ is a Dedekind ring.
- (3) A_b is a Dedekind ring.
- (4) A_b is an r -Noetherian ring.
- (5) A_b is a Krull ring.
- (6) A_b is an r -principal ideal ring.

Let $*$ be a star operation on R . If, for each finitely generated regular ideal I of R , there exists a finitely generated regular fractional ideal J such that $(IJ)^* = R$, then R is called a Prüfer $*$ -multiplication ring.

Let P be a prime ideal of R . Then we set $R_{[P]} = \{x \in q(R) \mid sx \in R\}$

for some $s \in R - P$.

Theorem 24 Let $*$ be an e.a.b. star operation on A . Let $N = \{g \in A[X; S] \mid g \text{ is regular, and } c(g)^* = A\}$. The followings are equivalent.

- (1) A is a Prüfer $*$ -multiplication ring.
- (2) A_* is a quotient ring of $A[X; S]$ with respect to a regular multiplicative subset.
- (3) If V is a valuation overring of A_* , there exists a prime ideal P of A which satisfies the following condition: $A_{[P]}$ is a valuation overring of A , and $V = A[X; S]_{[PA[X; S]]}$.
- (4) A_* is a flat $A[X; S]$ -module.
- (5) $A[X; S]_N$ is a Prüfer ring.

Let $f = \sum a_i X^{s_i}$, where each $a_i \neq 0$ and $s_i \neq s_j$ for $i \neq j$. We set $e(f) = \cup(S + s_i)$.

Theorem 25 Let $*$ be an e.a.b. star operation on S , $G = q(S)$, and let K be a field. We set $S_* = \{f/g \mid f, g \in K[X; S] - \{0\}, e(f)^* \subset e(g)^*\} \cup \{0\}$.

- (1) S_* is an overring of $K[X; S]$, and $S_* \cap G = S$.
- (2) S_* is a Bezout ring.
- (3) If I is a finitely generated ideal of S , then $(IS_*) \cap G = I^*$, and $IS_* = I^* S_*$.

For an e.a.b. semiatar operation $*$ on A (or on S), we may naturally define Kronecker function ring A_* (or S_*). Moreover, we may show the similar results to those for star operations.